Pegasus：
一个分布式KV系统的设计过程

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关于我

姓名：覃左言

经历：腾讯/百度/小米

关注：基础架构、分布式系统

爱好：运动、开源

开发过微服务框架

写过RPC框架：https://github.com/baidu/sofa-pbrpc

参与过分布式框架：https://github.com/Microsoft/rDSN

正在做KV存储系统：https://github.com/XiaoMi/pegasus

大纲

- 背景
- 设计
- 总结

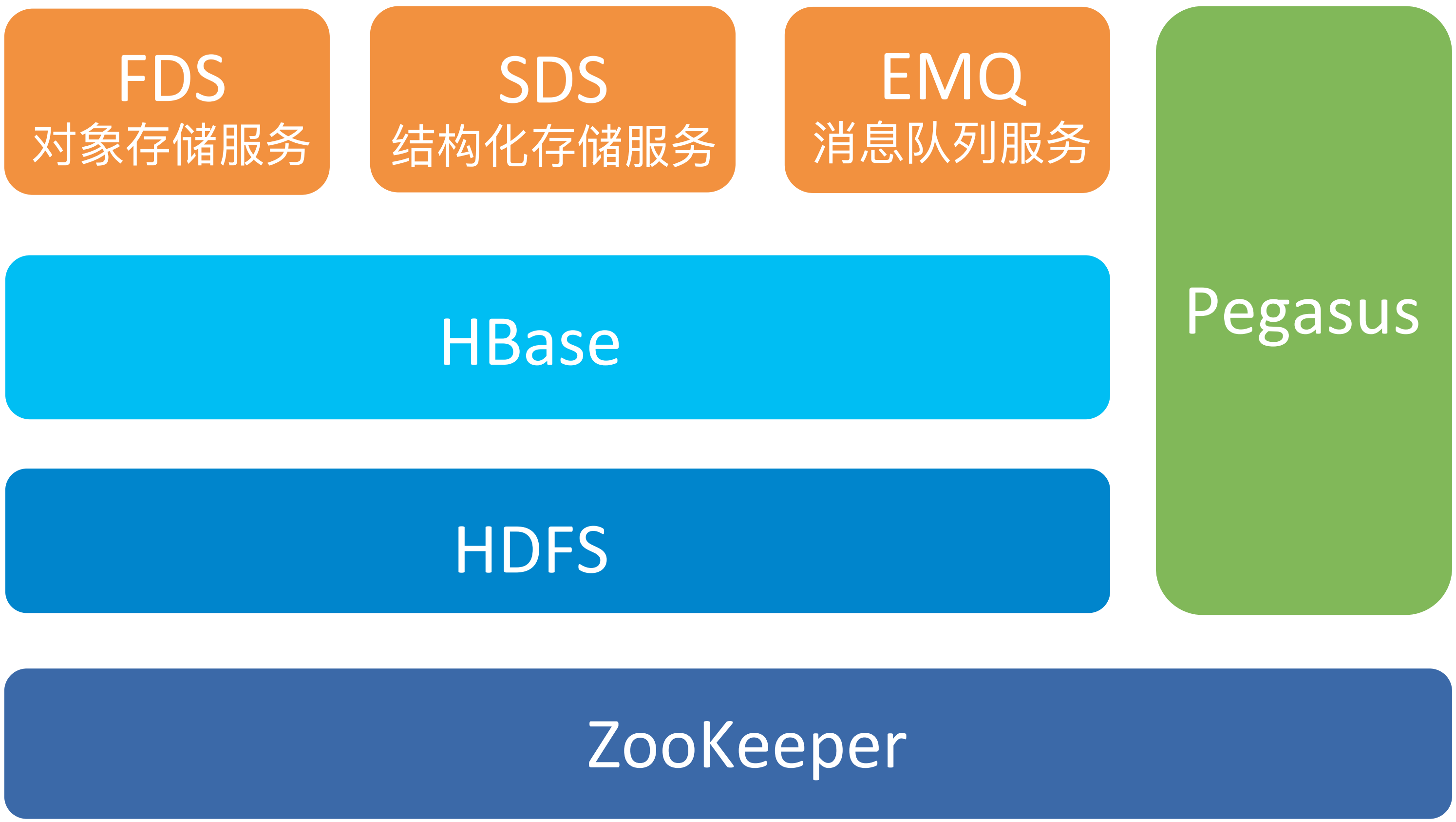
大纲

背景

设计

总结

Storage Service in Xiaomi



Storage Service in Xiaomi

10PB级

上百个业务

数百TB/day

数万亿行

>99.95%

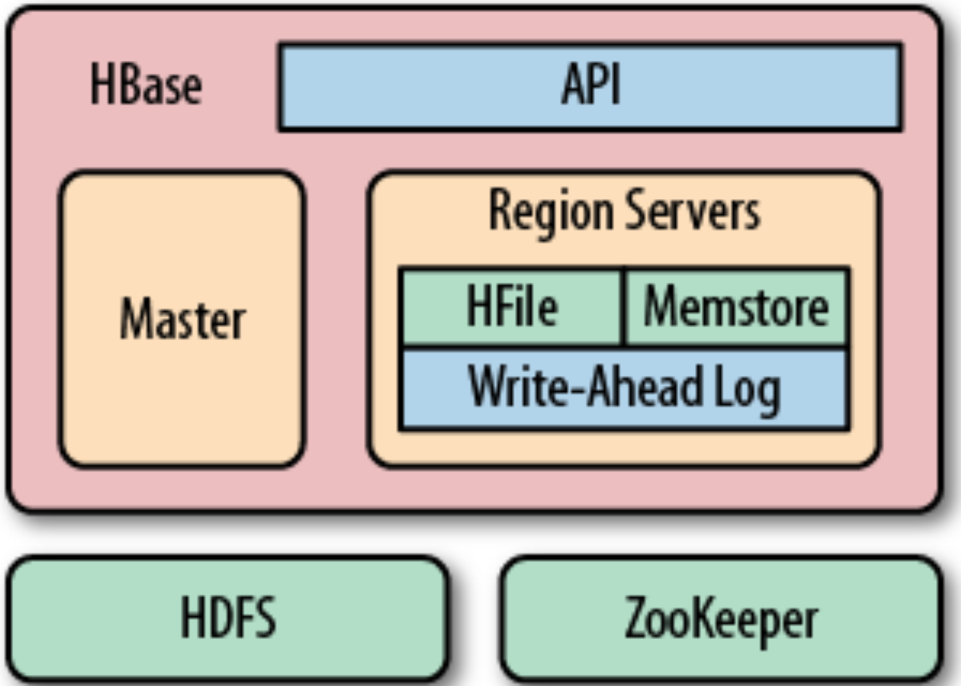
千万级QPS

5 HBase Committers

HBase Is Good, but Not Enough

- Layered Structure
- Weak Data Locality
- Longtime Recovery
- JVM Garbage Collection

可用性　　性能



What We Want

高可用

高性能

强一致

易使用

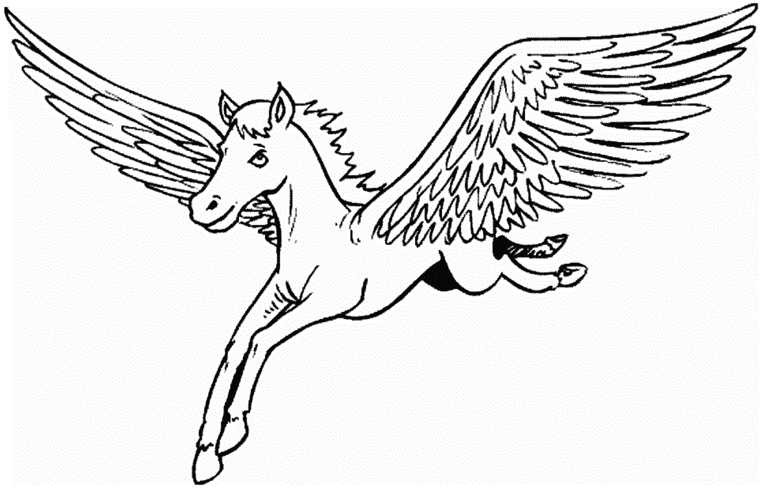
目标用户

- 对延迟较敏感的在线业务：广告、支付
- 对可用性要求很高
- 希望提供强一致性的语义

What We Did

Pegasus

一个高可用、高性能、强一致的分布式KV存储系统



大纲

背景

设计

总结

Many Choices ...

数据视图：KV系统 还是 表格系统?

数据分布：Hash 还是 Range?

系统架构：Centralized 还是 De-Centralized?

实现语言：C++、Java 还是 Go？

存储介质：HDD、SSD 还是 Memory？

一致性协议：Paxos、Raft 还是其他？

… …

围绕需求 | 先做容易的选择 | 不要太纠结 | 留有切换的余地

Basic Choices

实现语言：C++ ~~Java~~
- Java有GC问题
- C++性能高，风险小

存储介质：SSD ~~HDD~~ ~~Memory~~
- 性能、成本

单机引擎：RocksDB ~~BDB~~ ~~LevelDB~~
- LSMT（Log Structured Merge Tree）保证写性能
- 针对SSD和多核优化

性能

开发难度

风险

Model Choices

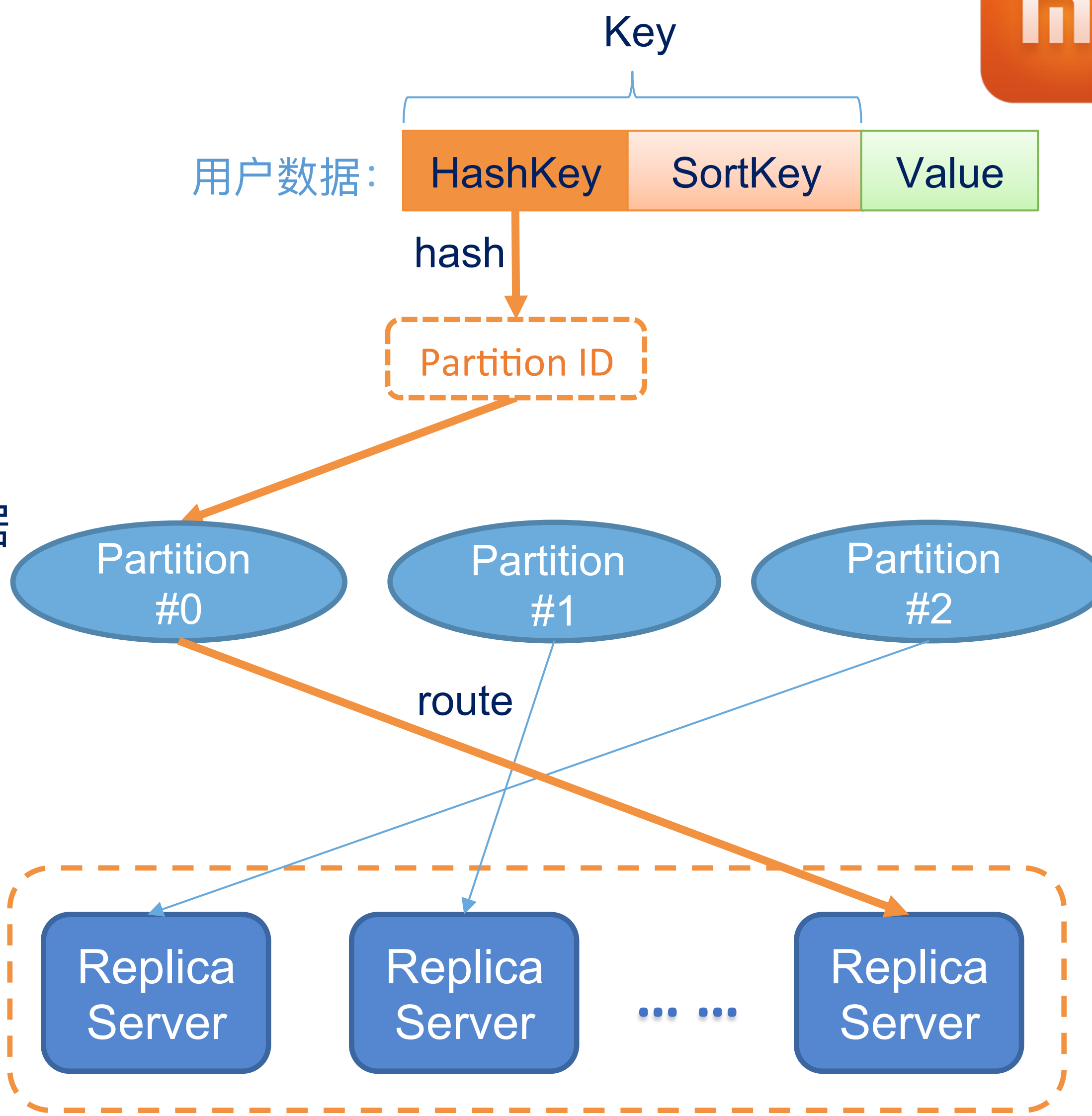
数据视图：KV系统 ~~Tabular系统~~
- 关注点在架构可行性
- KV系统更易实现
- 将来可改造为Tabular系统

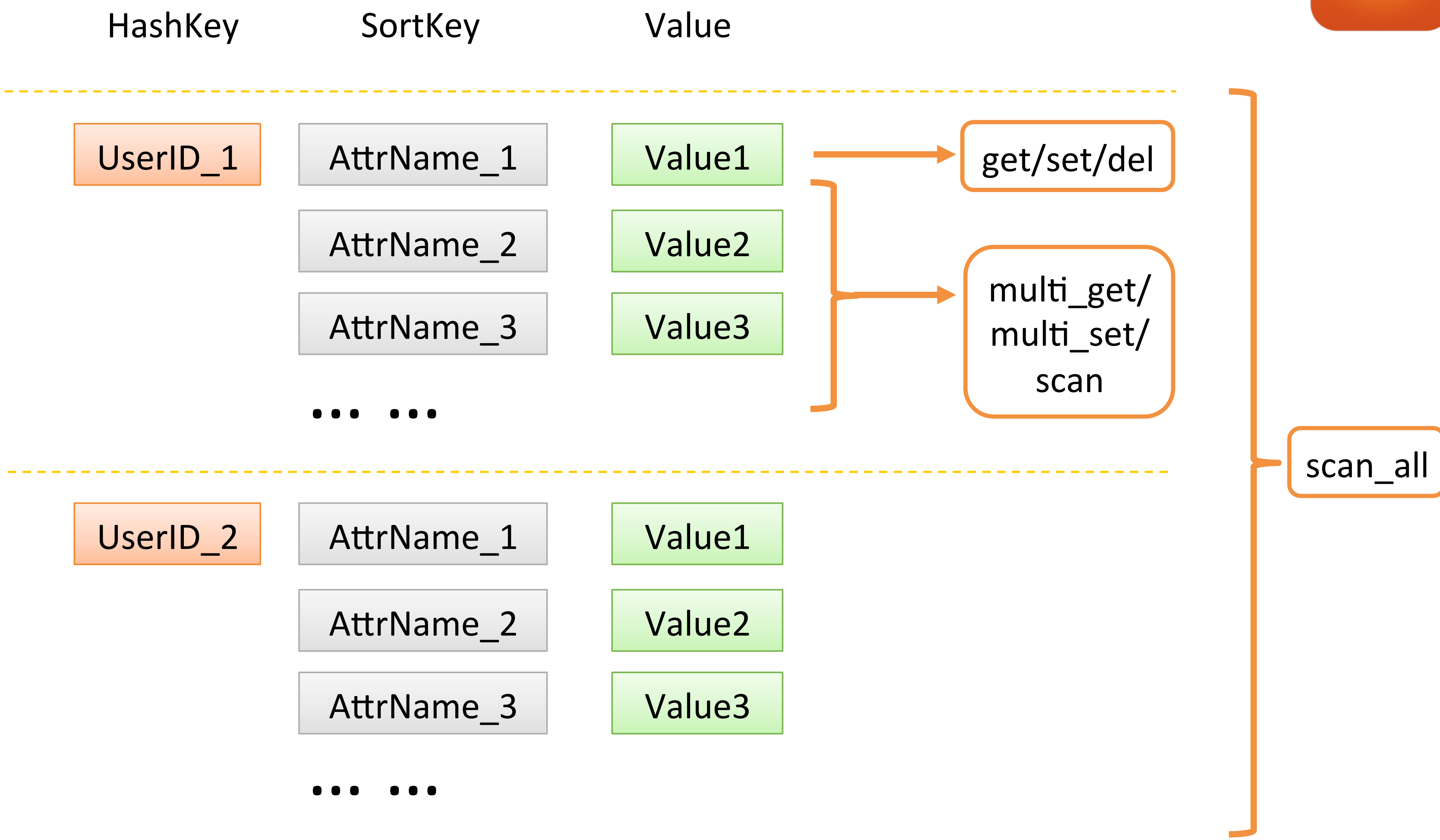
数据分布：固定Hash分片 ~~一致性Hash~~ ~~Range分片~~
- 实现简单
- 数据倾斜：合理设计Hash键和Hash函数
- 可伸缩性：预设 Partition Count 远大于 Server Count
- 热点问题：Hash分片和Range分片都不易解决

数据模型

- 组合主键： HashKey + SortKey
- HashKey用于Hash分片
- 同一个分片(Partition)中的数据按照 **[HashKey + SortKey]** 排序
- 利用Table进行空间隔离
- 随着业务需求增加功能

简单　灵活




HashKey
SortKey
Value
UserID_1
AttrName_1
Value1
AttrName_2
Value2
AttrName_3
Value3
… …
get/set/del
multi_get/
multi_set/
scan
scan_all
UserID_2
AttrName_1
Value1
AttrName_2
Value2
AttrName_3
Value3
… …

数据接口

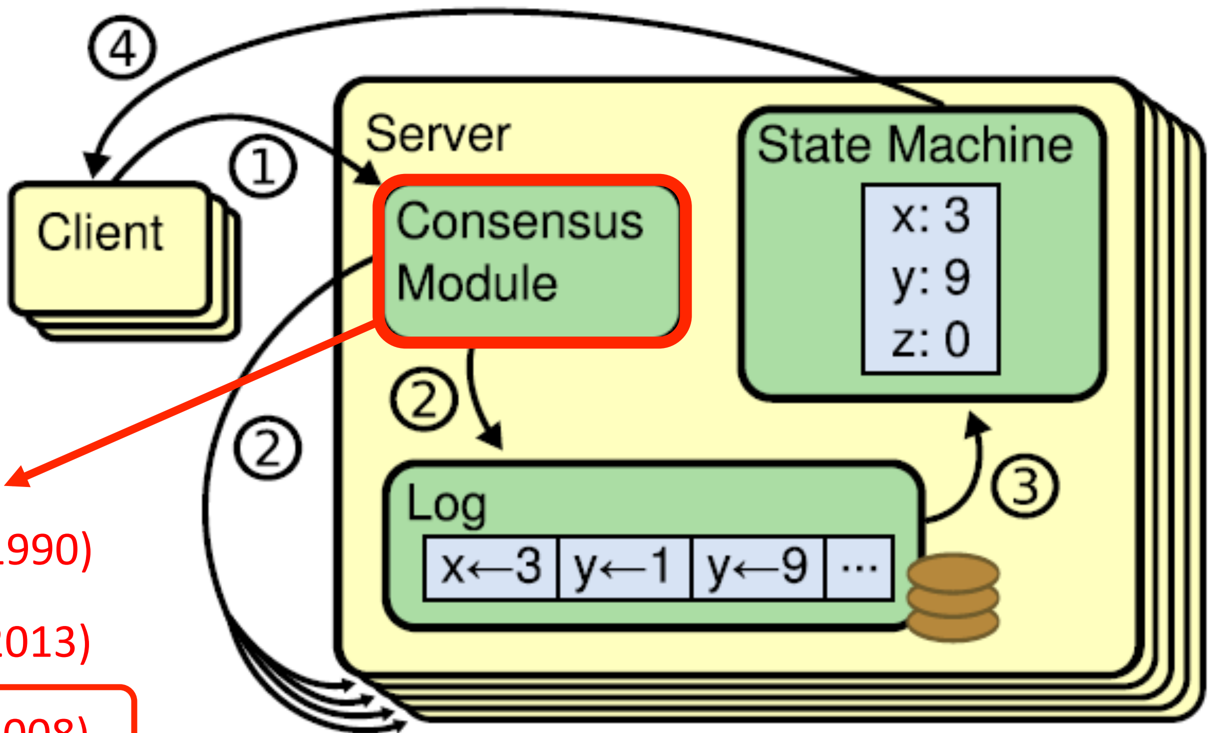
- get(HashKey, SortKey) → Value　　读单条数据
- set(HashKey, SortKey, Value, TTL) → Bool　　写单条数据
- del(HashKey, SortKey) → Bool　　删单条数据
- multi_get(HashKey, SortKey[]) → Value[]　　读相同HashKey的多条数据
- multi_set(HashKey, SortKey[], Value[]) → Bool　　写相同HashKey的多条数据
- scan(HashKey, SortKeyBegin, SortKeyEnd) → Iterator　　扫描相同HashKey的数据
- scan_all() → Iterator　　扫描全部数据

Redis适配

SET　SETEX　GET　DEL　INCR　INCRBY　DECR　DECRBY　TTL

易使用

Consensus Algorithm Choices

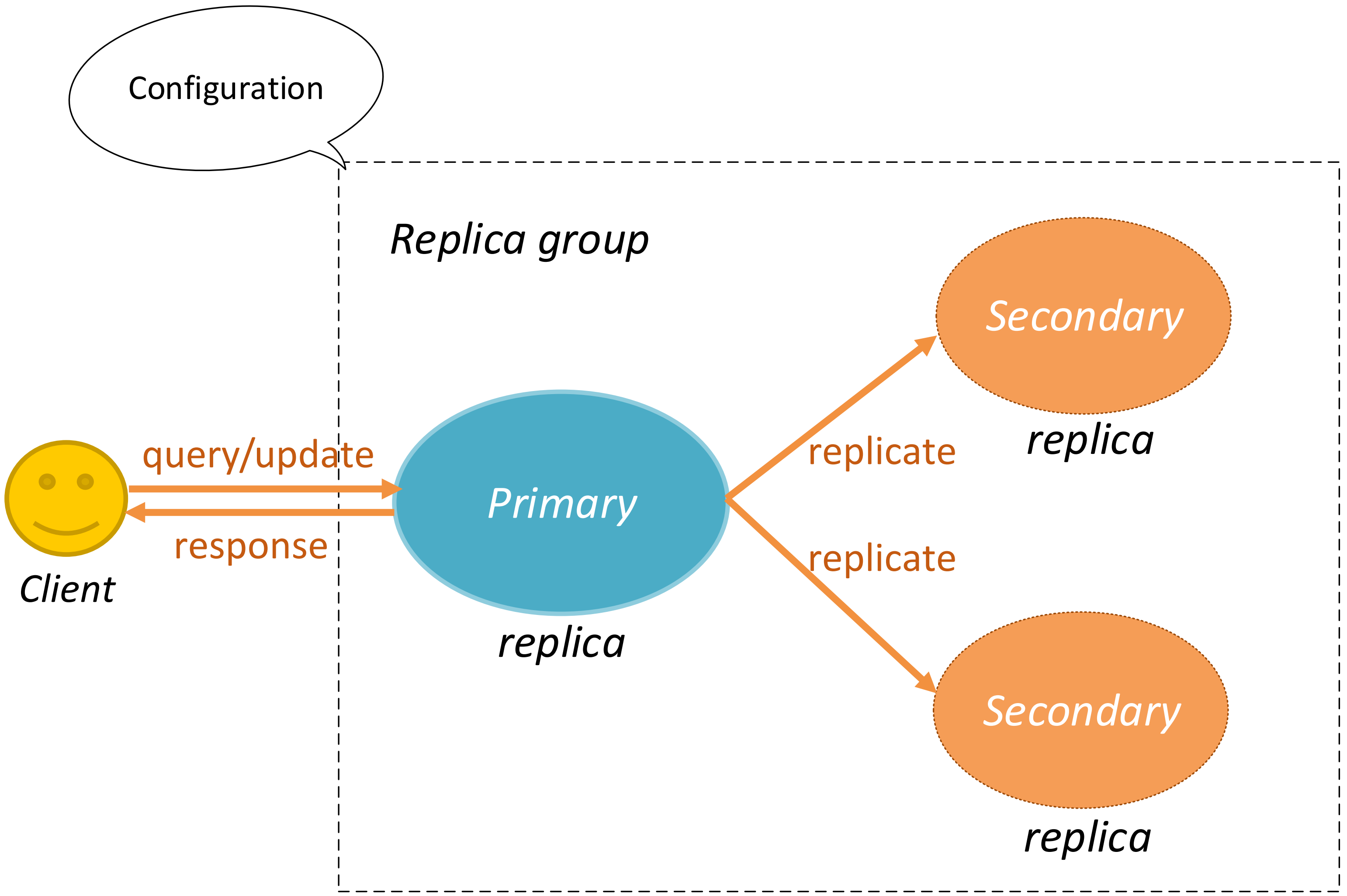


Paxos (1990)

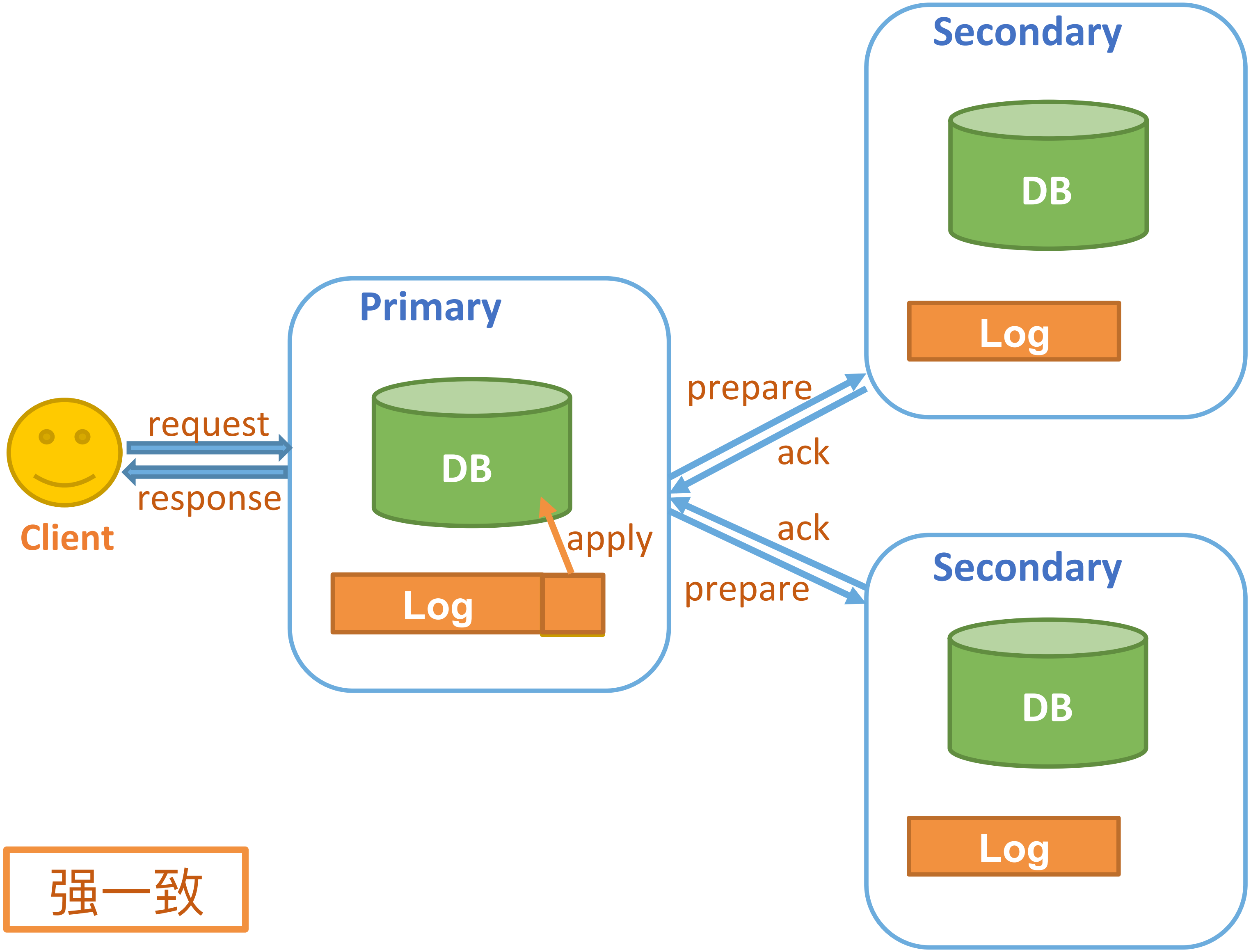
Raft (2013)

PacificA (2008)

Replicated State Machine Architecture



Primary/Backup Paradigm of PacificA

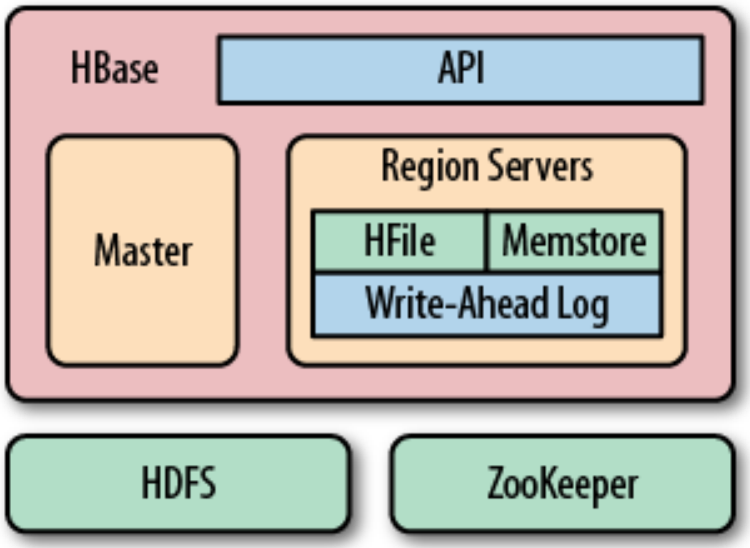


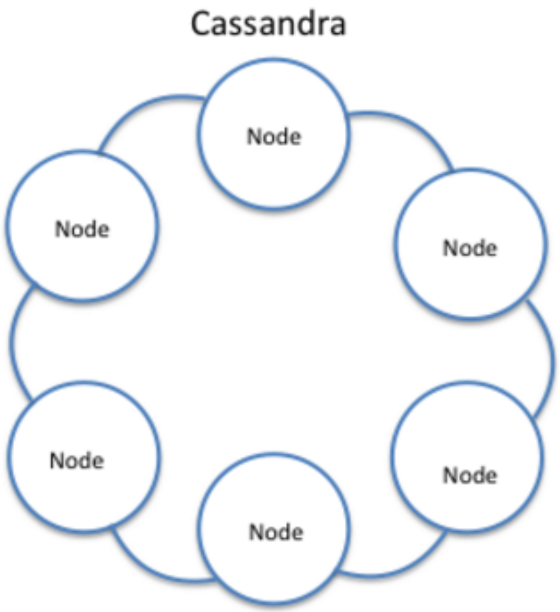
强一致

Two-Phrase Commit of PacificA

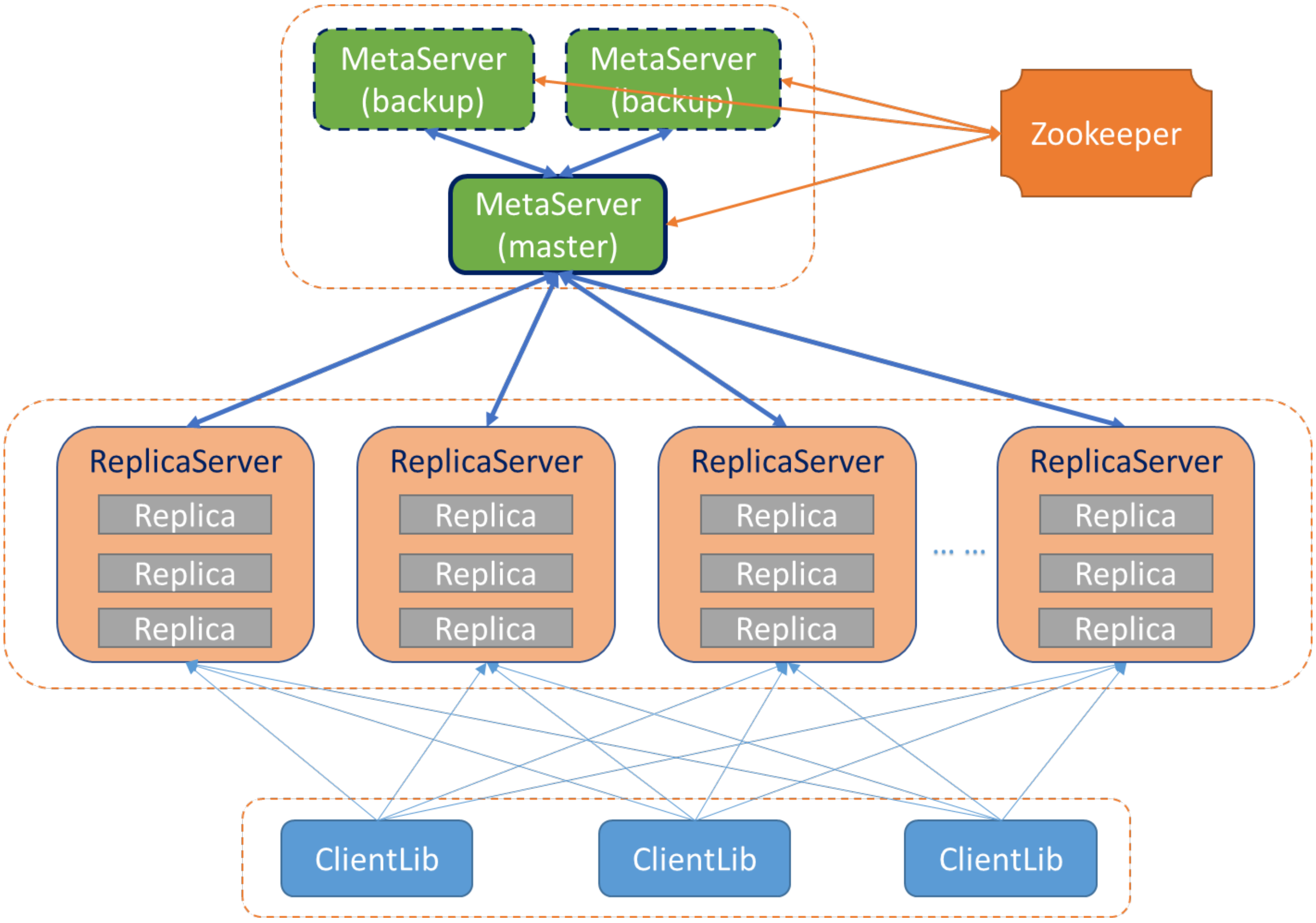
Architecture Choices

Centralized Vs. Decentralized



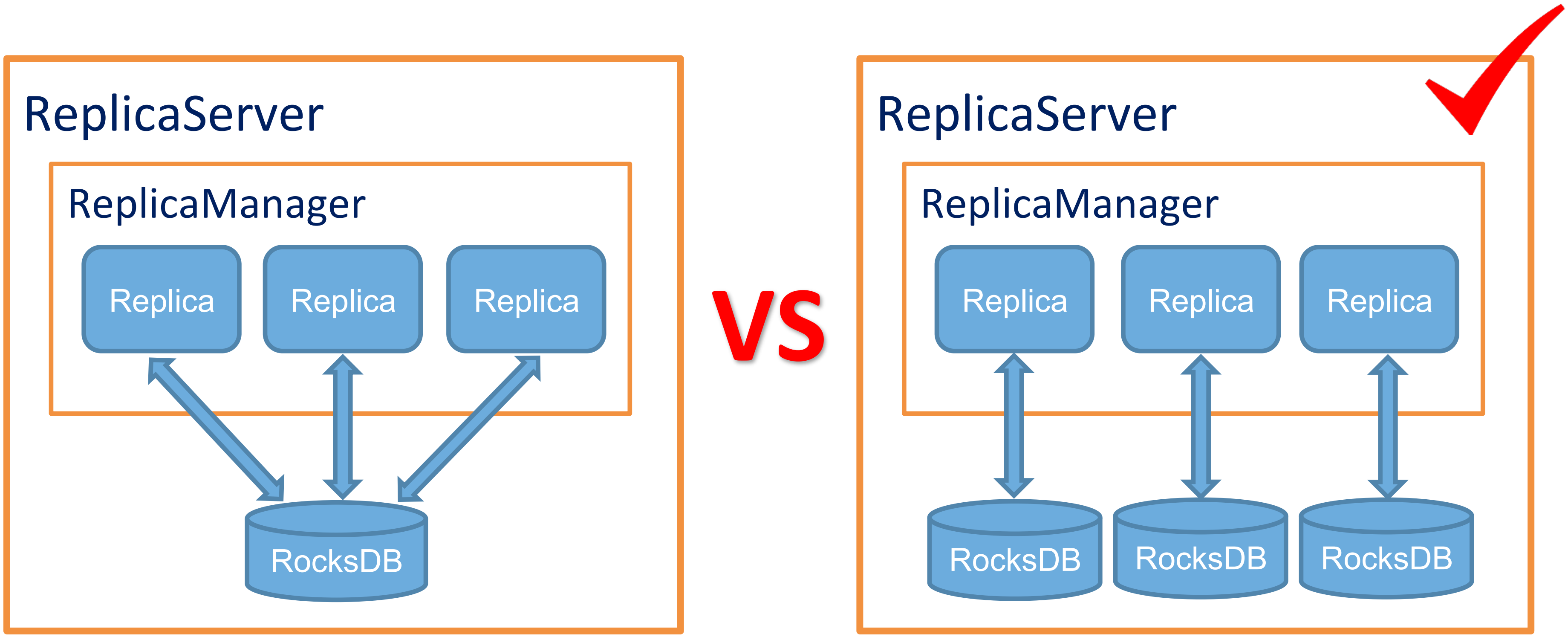


Layered Vs. Integrated

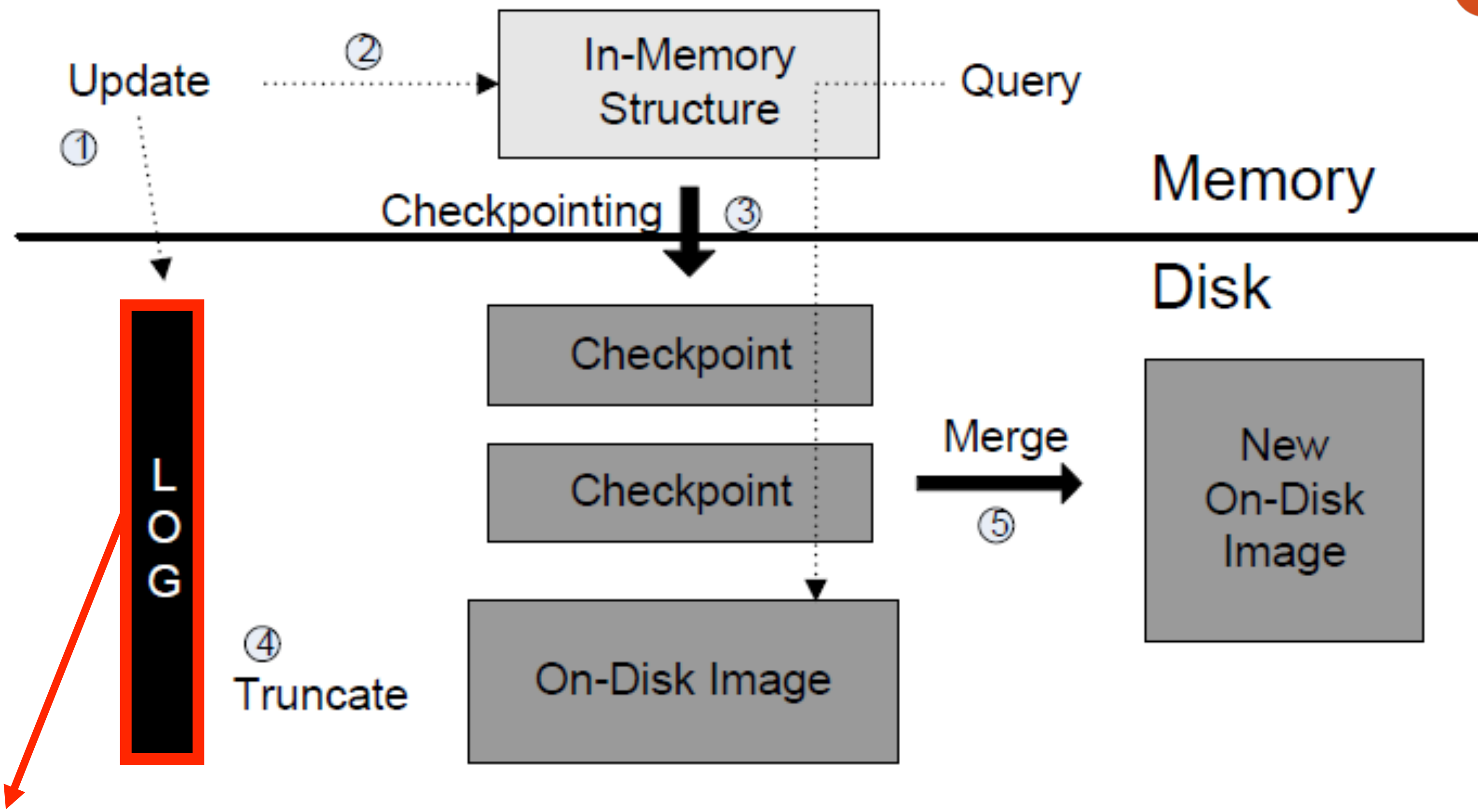


Pegasus Architecture

ReplicaServer Design Choices



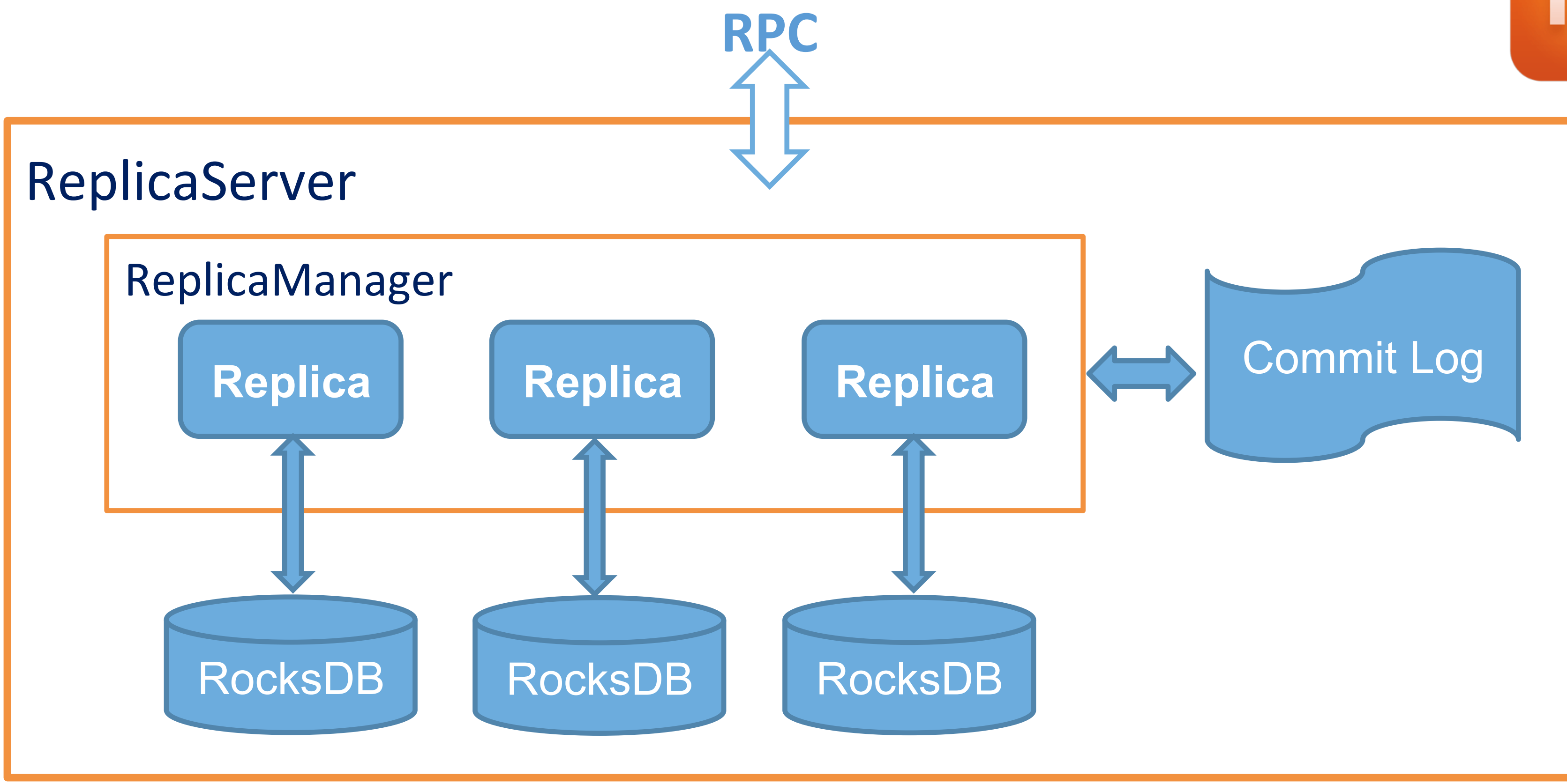
- 避免不同Table/Partition的数据相互影响
- 更容易实现 Load Balance 和 Drop Table
- 方便将数据分散到多个SSD盘，提高并发能力



Make commit log shared by all replicas

- 减少 write compete
- 适合 batch write

RocksDB: Log-Based Storage System

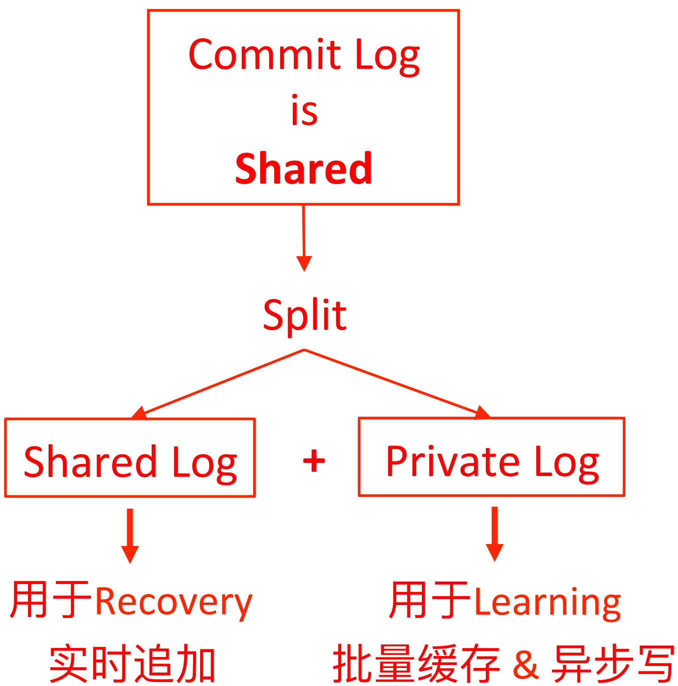


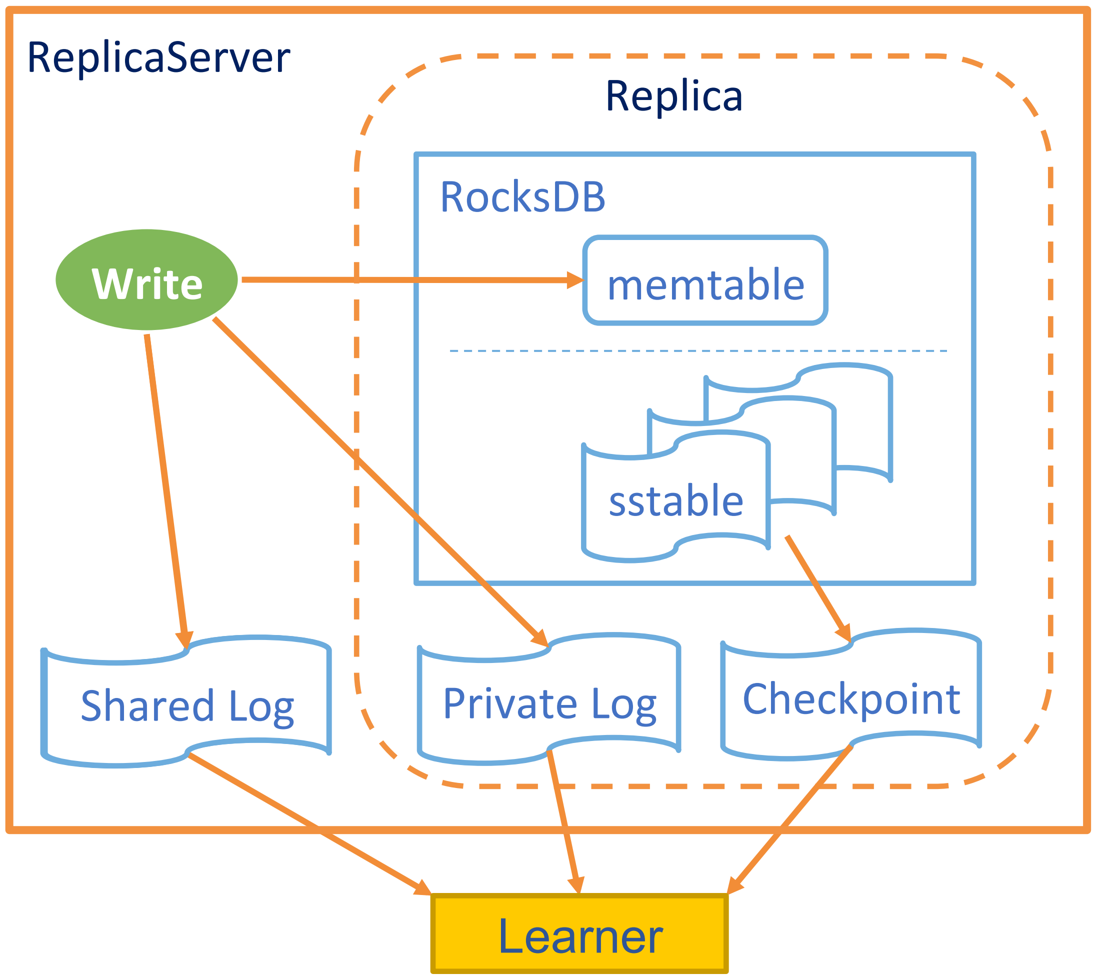
- ReplicaServer管理多个Replica
- 每个Replica 独享 RocksDB
- 所有Replica 共享 Commit Log

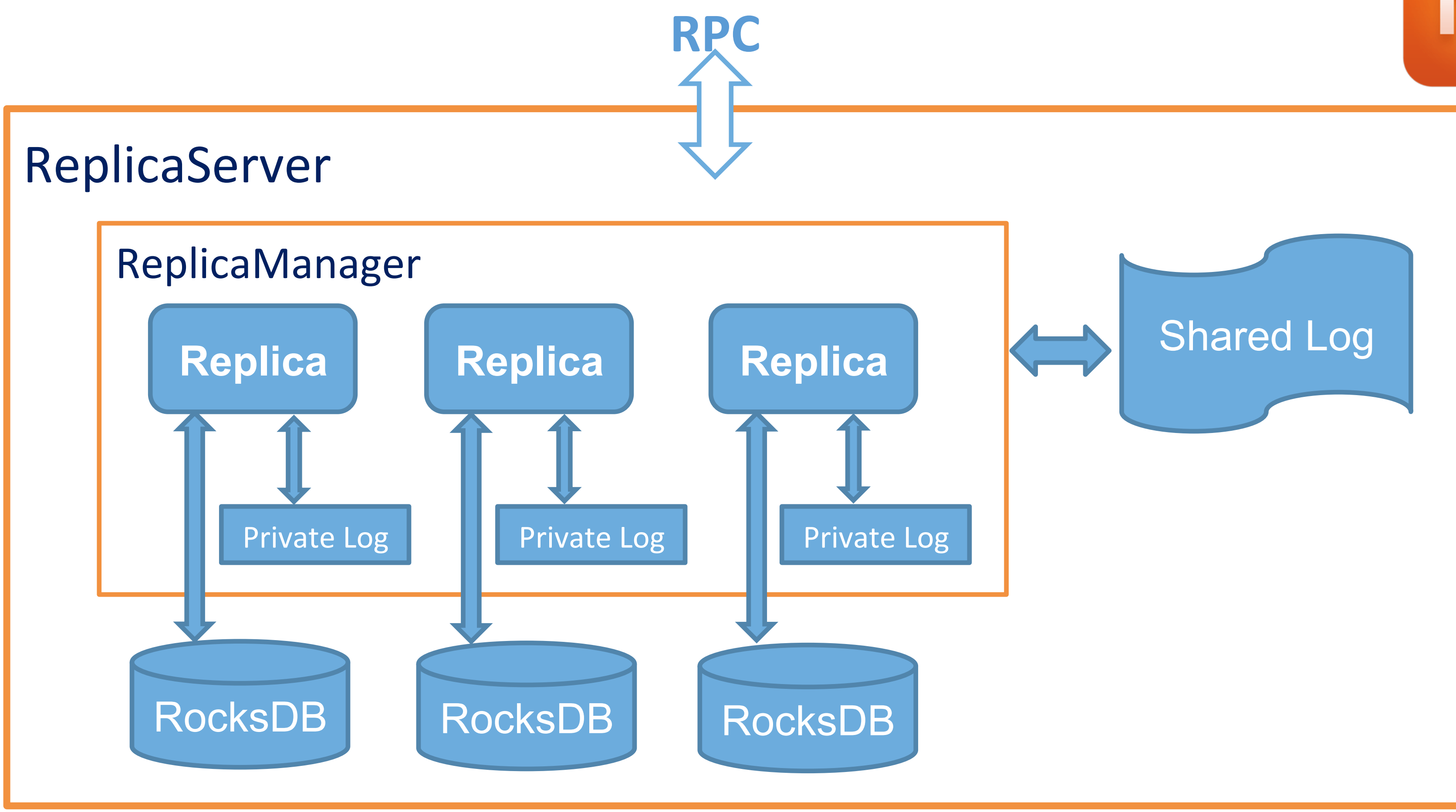
Architecture of ReplicaServer

Considering Catch-Up …

- How to catch up:
  - Learn checkpoint
  - Learn commit log





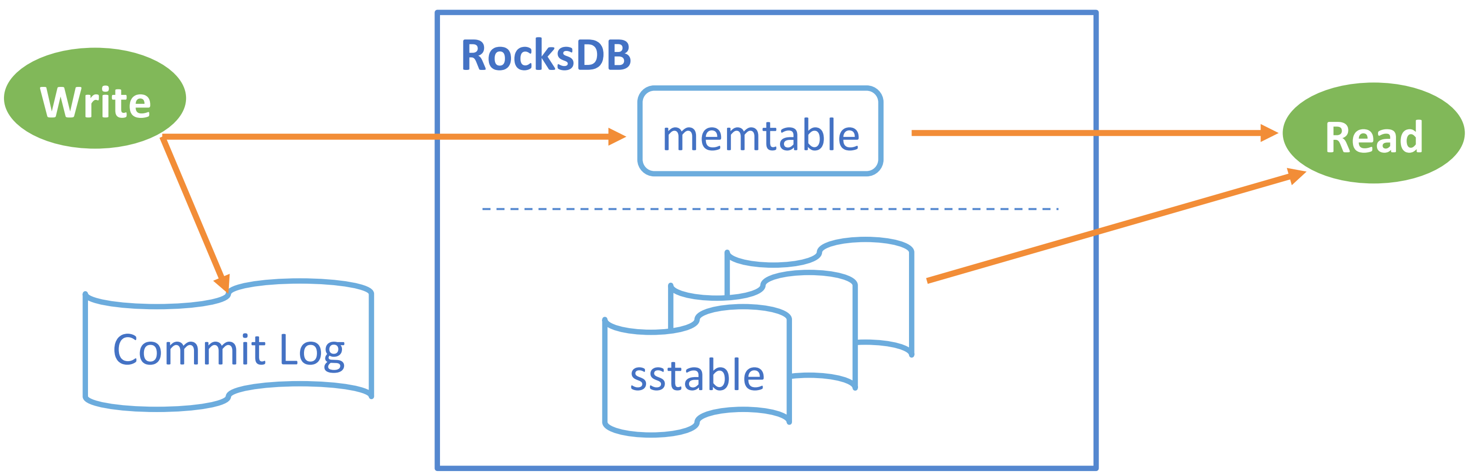


- Shared Log for Recovery
- Private Log for Learning

Improved Architecture of ReplicaServer

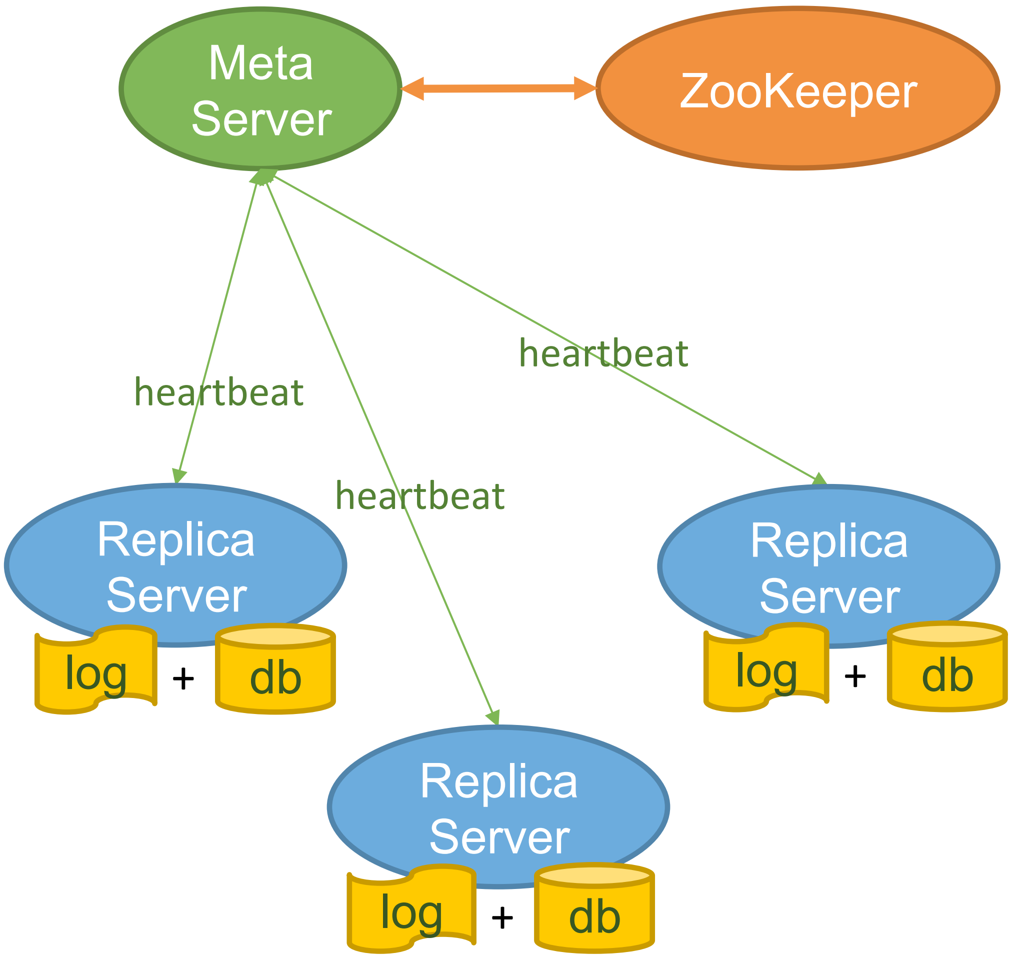
RocksDB as Storage Engine

- 只使用Default Column Family
- 禁用Write Ahead Log
- 并发控制：写操作在单线程中串行执行，读操作允许多线程并发执行
- 数据扩展：写操作会额外传入数据在Log中的序号（Decree）
- 优化快照：同步 → 异步，避免同步过程阻塞写操作



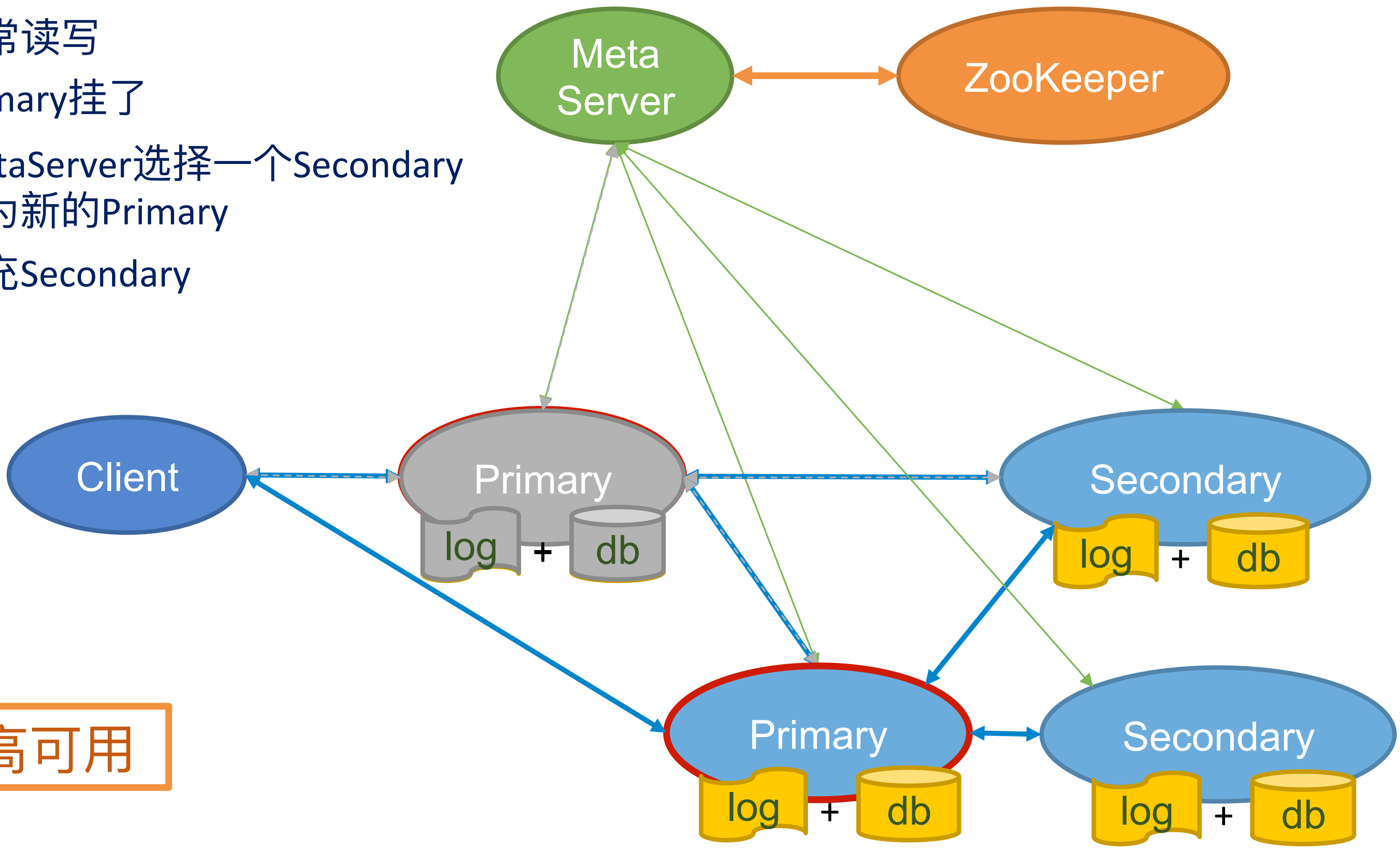
Failover

- MetaServer和所有的ReplicaServer维持心跳
- Failure Detection通过心跳来实现
- Failover有三种类型：
    - Primary Failover
    - Secondary Failover
    - MetaServer Failover



Primary Failover

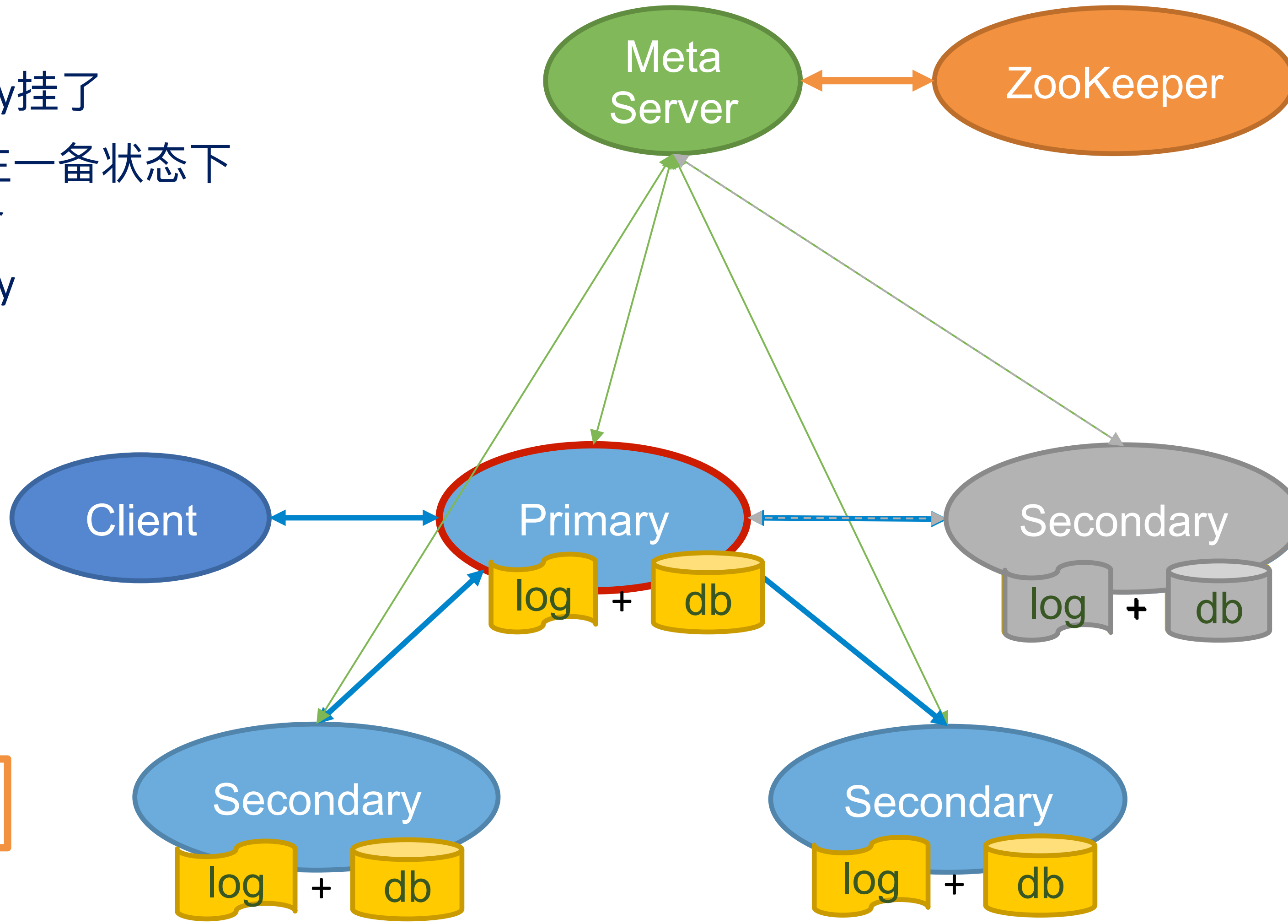
1. 正常读写
2. Primary挂了
3. MetaServer选择一个Secondary成为新的Primary
4. 补充Secondary



高可用

Secondary Failover

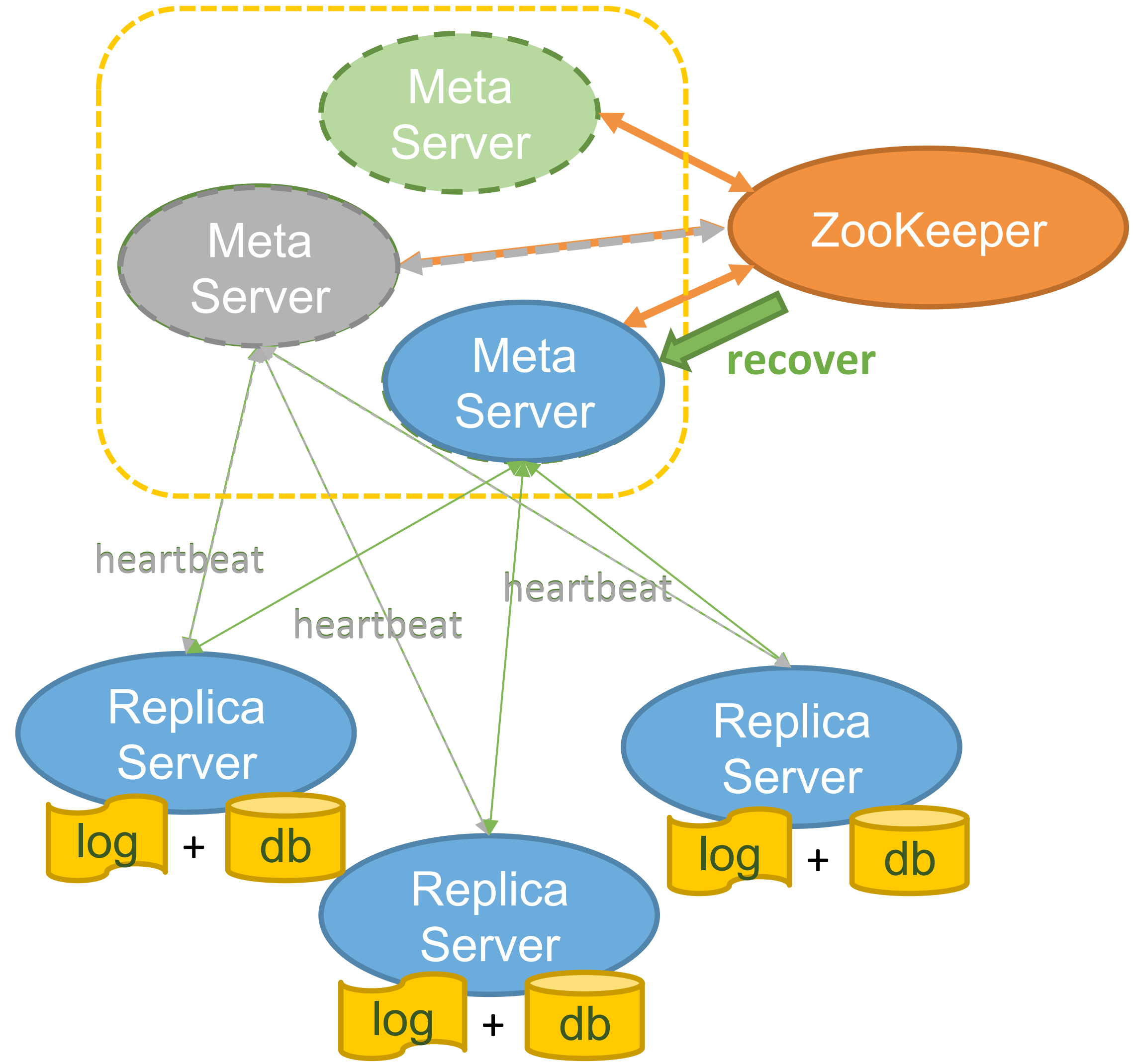
1. 正常读写
2. 某个Secondary挂了
3. Primary在一主一备状态下继续提供服务
4. 补充Secondary



高可用

MetaServer Failover

1. 主MetaServer和所有的ReplicaServer维持心跳
2. 主MetaServer挂了
3. 某个备MetaServer通过ZooKeeper抢主成为新的主MetaServer
4. 从ZooKeeper恢复状态
5. 重新和所有ReplicaServer建立心跳



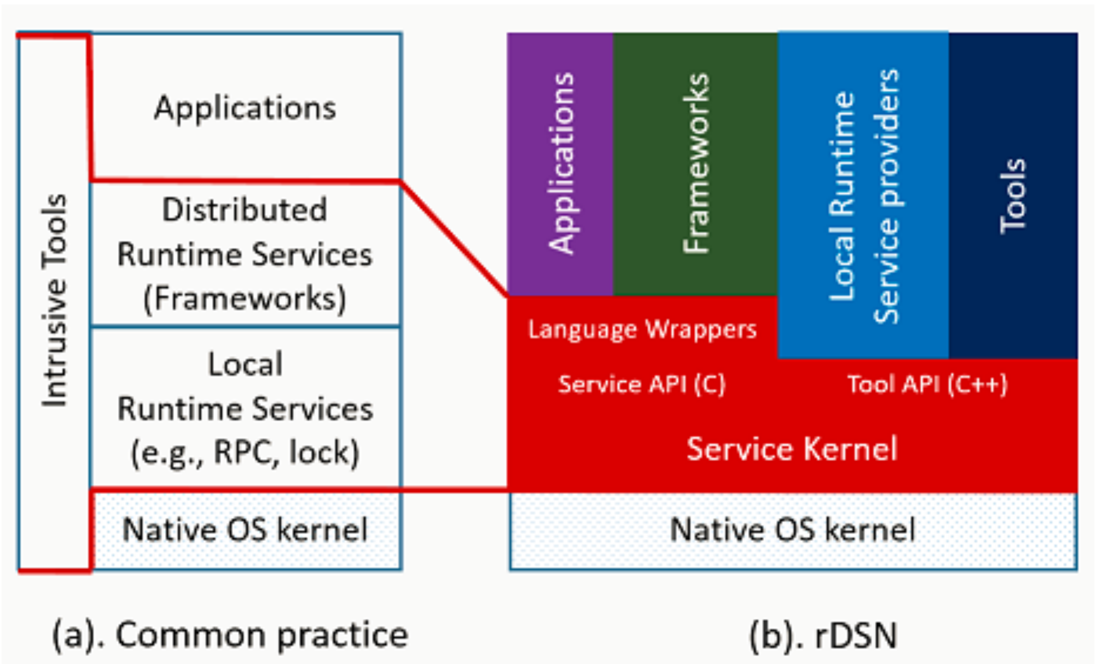
高可用

Data Safety

- Table软删除
  - Table删除后，数据会保留一段时间，防止误删除
- 元数据恢复
  - 元数据丢失或者损坏时，从各ReplicaServer收集并重建元数据
- 定期冷备份
  - 数据定期备份到多种介质，譬如HDFS
  - 在需要的时候快速恢复
- 跨机房热备
  - 在多个机房部署集群
  - 采用异步复制的方式实时同步数据
  - 多集群可同时对外提供服务

Engineering …

- Built on rDSN (Robust Distributed System Nucleus) framework
  - https://github.com/Microsoft/rDSN



Microkernel Architecture

Most Things Are Pluggable

Lock | RPC | AIO | Timer

Logging | Replication | … …

Friendly for Testing, Debugging and Monitoring

How to Test

- Unit Test
- Integration Test
- Simulation Test
    - Simulate cluster in
    - Processing can be r
- Scenario Test
    - Declarative language
    - Construct different scenarios (executing paths / corner cases)

```
# Scenaria 201: inject on_aio_call of primary log write

set:load_balance_for_test=1    设置属性

# wait for server ready
config:{3,r1,[r2,r3]}
state:{{r1,pri,3,0},{r2,sec,3,0},{r3,sec,3,0}}    等待状态

# begin to write k1
client:begin_write:id=1,key=k1,value=v1,timeout=0    发起动作

# inject aio error on primary r1
inject:on_aio_call:node=r1,task_code=WRITE_LOG    注入错误

# error should occur on r1
state:{{r1,err,3,0},{r2,sec,3,0},{r3,sec,3,0}}    等待状态

# r1 should drop itself
state:{{r2,sec,3,0},{r3,sec,3,0}}
config:{4,-,[r2,r3]}

# r2 will become the primary
state:{{r2,ina,4,0},{r3,sec,3,0}}
config:{5,r2,[r3]}

```

大纲

背景

设计

总结

Why ➡ How ➡ What

Many choices ...

Fit is the best

Pegasus是对HBase的有力补充

- 更优异的性能：C++、No GC、Data Locality
- 更高的可用性：No GC、Faster Failover
- 更轻量的部署：No HDFS、No ZooKeeper (in the future)
- 更简单的接口：Key-Value

Future Work

- PacificA → Raft
- Key-Value → Tabular
- Remove ZooKeeper Dependency
- Performance Tuning
- Improve Load Balance
- Cross Row Transaction
- Open Source

Thanks

个人微信号：

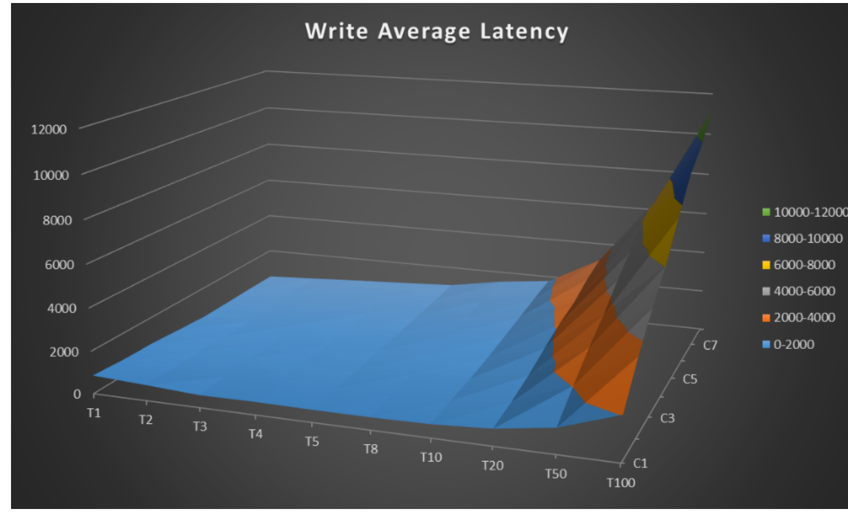
欢迎有志之士加入我们：分布式相关、人工智能相关

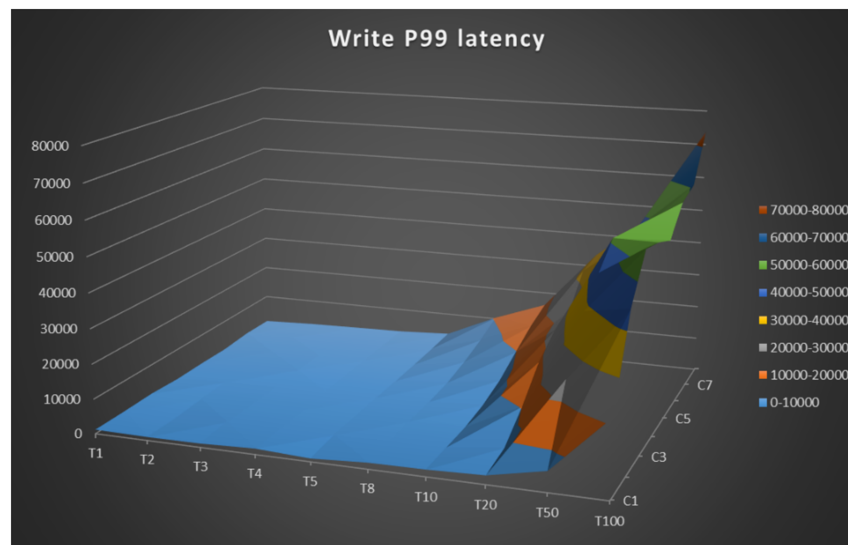
简历请发至邮箱：qinzuoyan@xiaomi.com

附录

Pegasus写性能

- 单机QPS 可达 1.5w+
- 单机QPS<1w 时，平均延迟<5ms
- 单机QPS<1w 时，P99 延迟<20ms

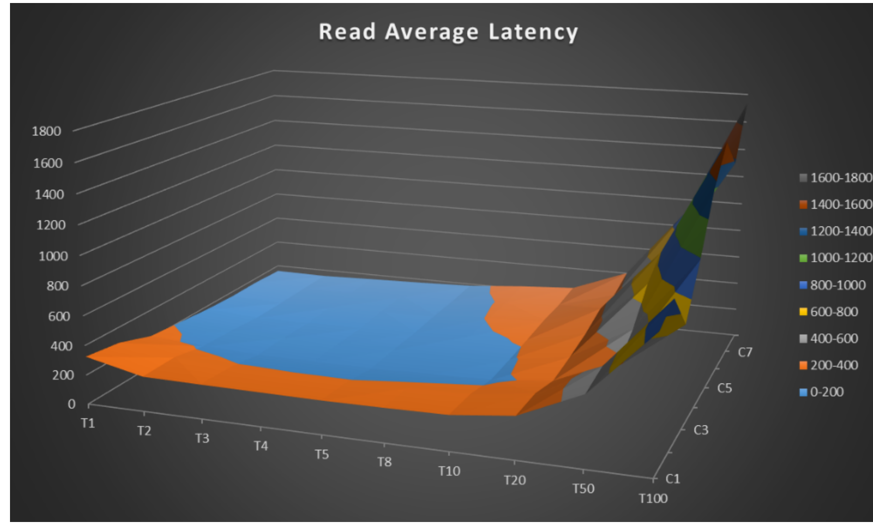


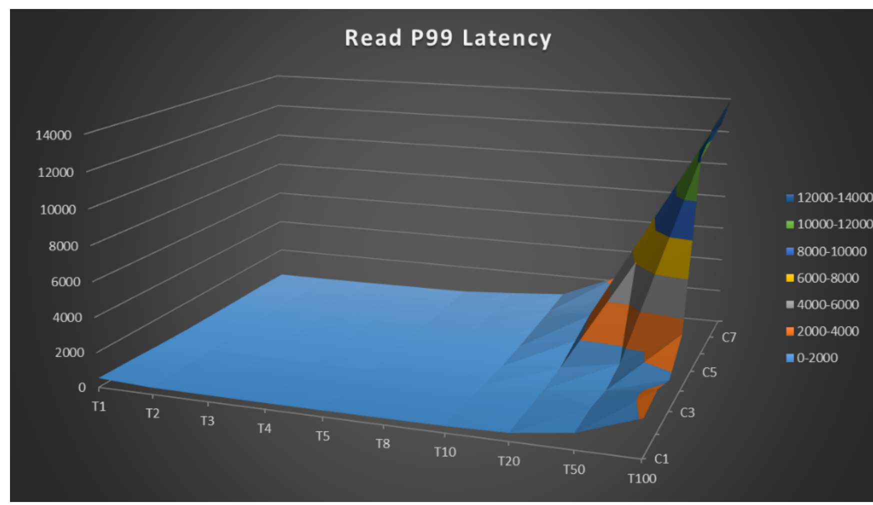


注：X轴T_n为单Client线程数，Y轴C_n为Client进程数，Z轴延迟单位为微妙，集群使用5个数据节点

Pegasus读性能

- 单机QPS 可达 10w+
- 单机QPS<5w 时，平均延迟<1ms
- 单机QPS<5w 时，P99 延迟<5ms

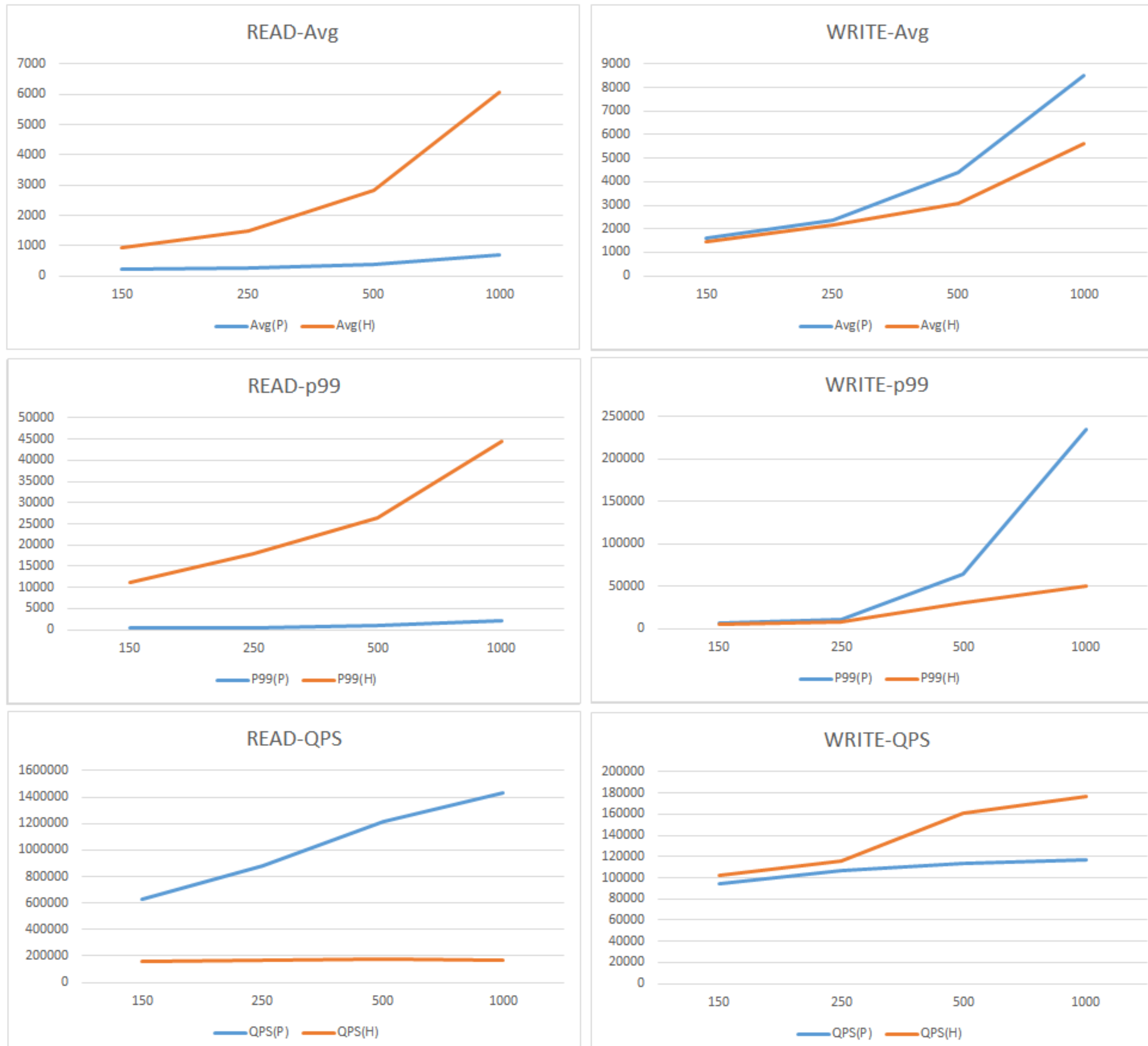




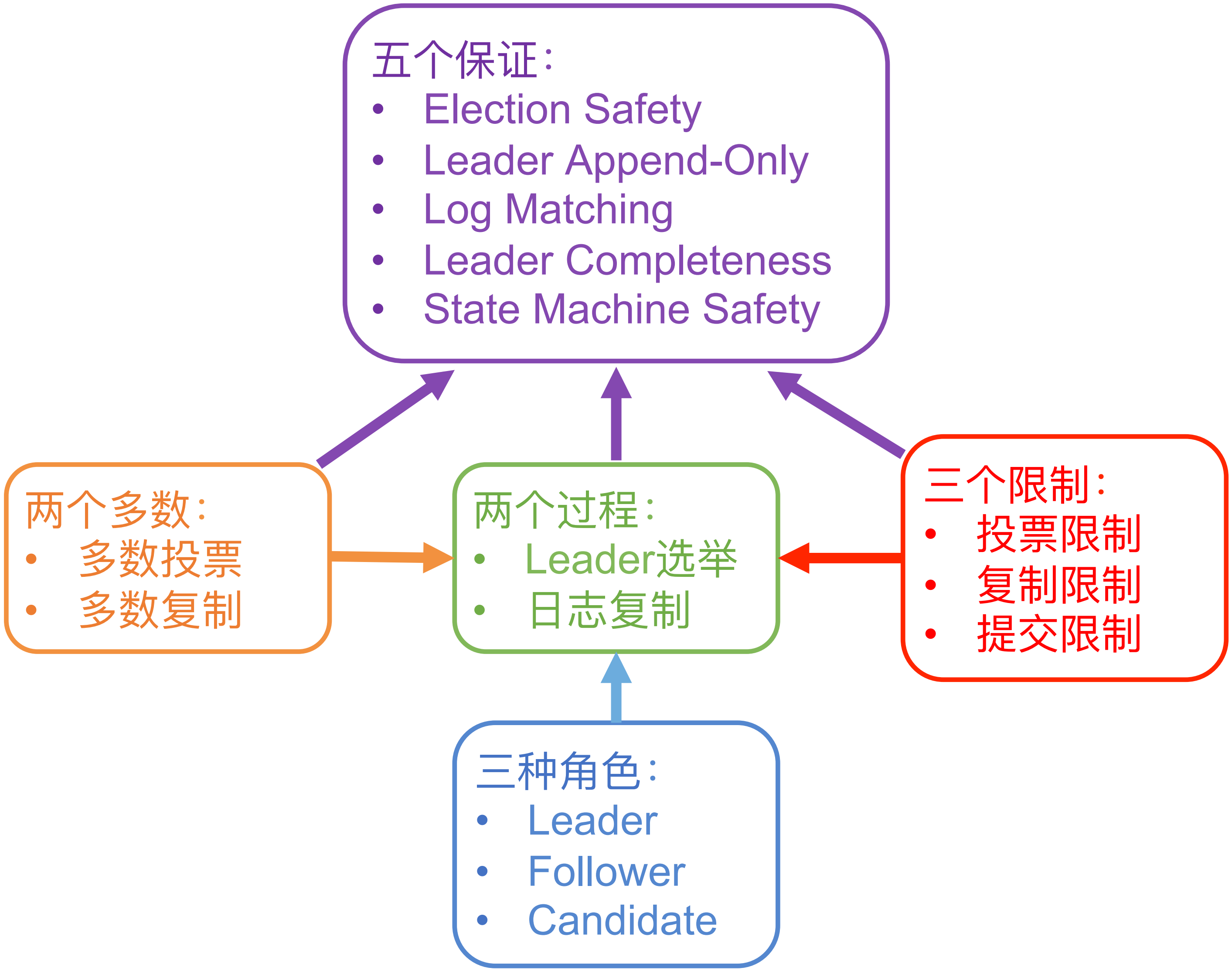
注：X轴T_n为单Client线程数，Y轴C_n为Client进程数，Z轴延迟单位为微妙，集群使用5个数据节点

对比HBase

- 读性能优势明显
- 写性能略差



注：蓝色曲线为Pegasus，红色曲线为HBase，延迟单位为微妙，集群使用10个数据节点



Raft Algorithm

Raft VS PacificA

Replicated State Machine

Strong Leader

Decomposition

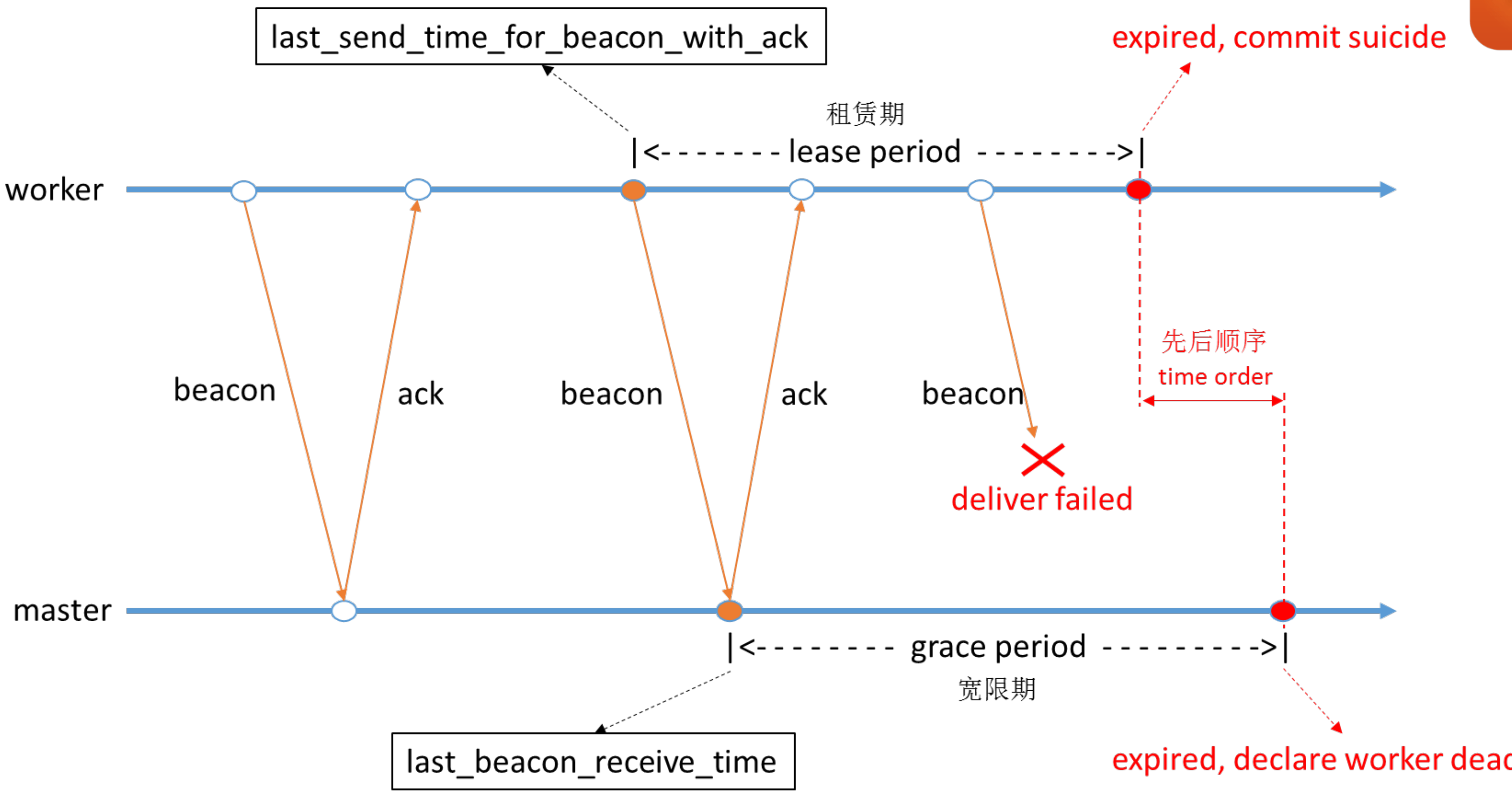
Two-Phrase Commit

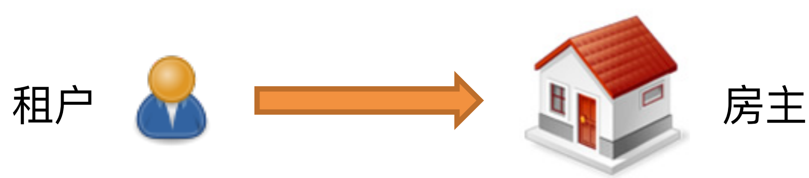
Logical Time

Heartbeat

Log-Based Storage System

	Raft	PacificA
Leader Election	Majority Vote	First Come First Served
Commit Condition	Majority Replication	Fully Replication
Safety Guarantee	Additional Restriction	Fully Replication



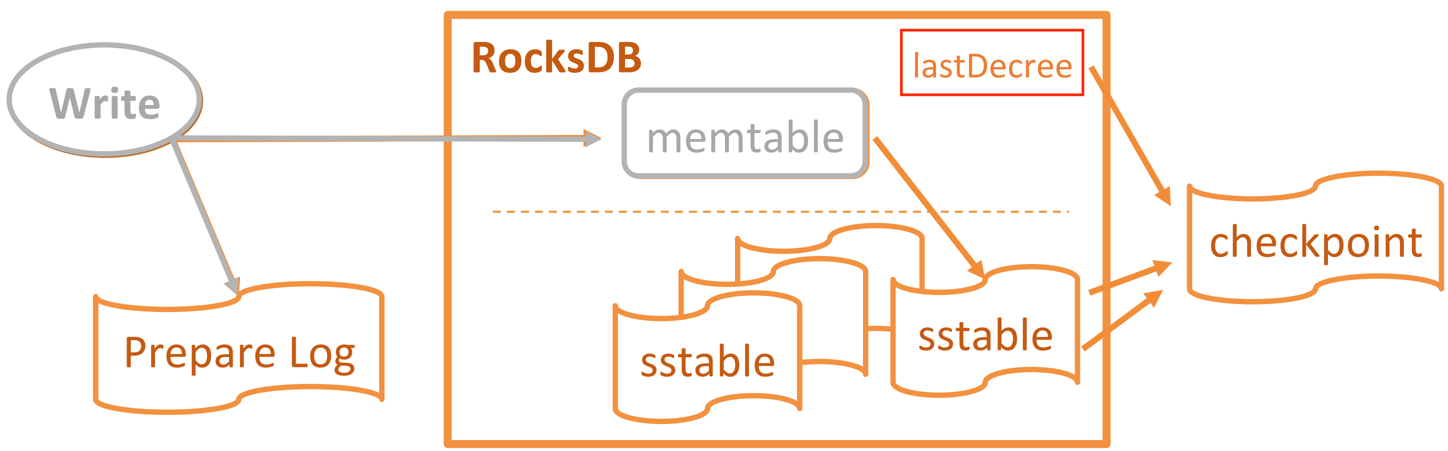


Lease-Based Failure Detection

RocksDB supports async-checkpoint

RocksDB本身支持 Sync-Checkpoint：

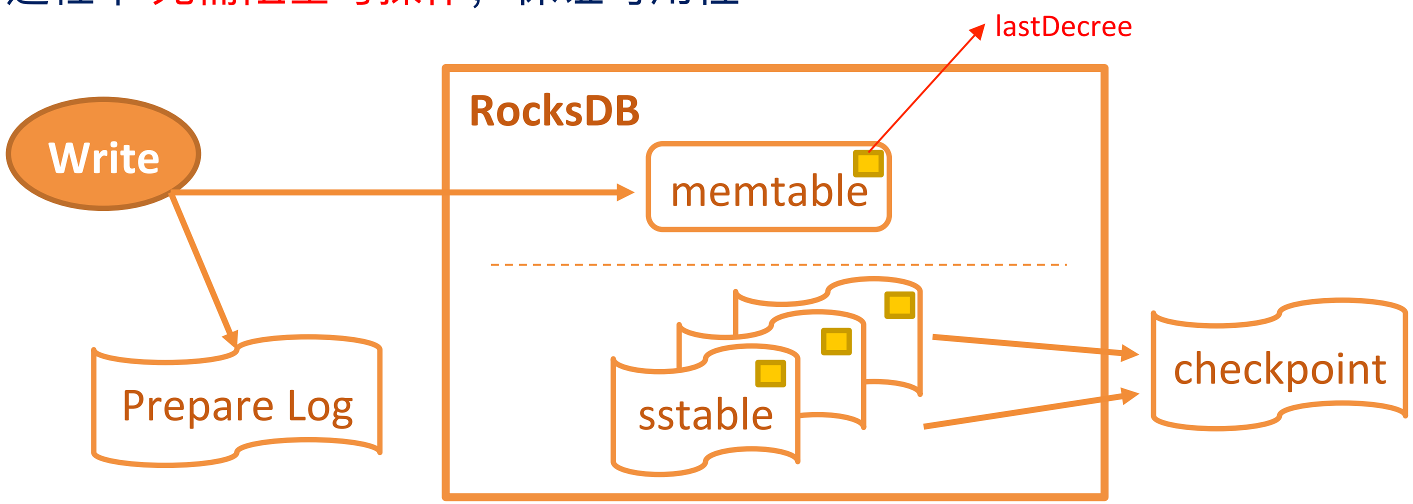
- RocksDB记录最后一次Write的 lastDecree
- 在Sync-Checkpoint时，需先 dump memtable，然后 同步等待 dump完成
- Dump完成后，将元数据和sstable拷贝至Checkpoint，然后使用 lastDecree 进行标记
- 在整个过程中 需阻塞写操作，降低可用性



RocksDB supports async-checkpoint

改进的RocksDB支持 Async-Checkpoint :

- RocksDB的memtable/sstable都会记录 自己当前的lastDecree
- 在Async-Checkpoint时，直接忽略memtable的数据，将元数据和sstable拷贝至Checkpoint，并使用所有sstable的 最大lastDecree 作为Checkpoint的decree标记
- 在整个过程中 无需阻塞写操作，保证可用性



参考

- PacificA Algorithm
  - https://www.microsoft.com/en-us/research/wp-content/uploads/2008/02/tr-2008-25.pdf
- Raft Algorithm
  - https://raft.github.io/raft.pdf
- rDSN Framework
  - https://github.com/Microsoft/rDSN
- Pegasus System
  - https://github.com/XiaoMi/pegasus (coming soon)